

Grazing-incidence measurements of L -shell line emission from highly charged Fe in the soft x-ray region

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Line emission from highly charged ions in the soft x-ray region represents an important diagnostic for high-temperature plasmas. The wavelength region of 10–30 Å is occupied by lines from the K -shell transitions in N through Ne and L -shell transitions in Ti through Ni. Crystal spectrometers have previously been used to investigate Fe line radiation under well controlled conditions using the LLNL electron beam ion trap facility in this wavelength region. To complement this work we have instituted a grazing-incidence spectrometer with a variable line-spaced, concave grating and a flat field of focus which is suited for a multichannel detector. Simultaneous observations of the Ne-like $\text{Fe}^{16+} n=3 \rightarrow 2$ transitions were made with this instrument and a flat-crystal spectrometer in order to establish the linear polarization of the Fe XVII lines. We present a description of the grating spectrometer and discuss its performance in comparison with Rowland circle based grazing incidence instruments. © 1998 American Institute of Physics. [S0034-6748(99)70201-7]

I. INTRODUCTION

Spectroscopy is a well established, integral branch of many fields involving high-temperature plasmas, such as astronomy, laser-matter interactions, and magnetic fusion. In most instances, the spectral line emission has been used to deduce the relevant plasma parameters from the line intensities. This includes the electron temperature and density, ion abundances and temperature, or plasma motion. Spectroscopic measurements in the soft x-ray region at the Livermore electron beam ion trap (EBIT) have utilized vacuum crystal spectrometers.^{1,2} Recently, new diagnostics have been developed to determine the polarization of the emitted lines^{1,3,4} which gives information on anisotropies of the electron distribution function in the plasma. The diagnostics were focused on x-ray lines, notably the K -shell emission from highly charged iron ions near 1.8 Å and implemented a “two crystal-spectrometer” technique. In the following we concentrate on the iron L -shell emission below 20 Å and extend our polarization diagnostics to the soft x-ray region by adding a grating spectrometer sensitive to the soft x-ray region to the instrumentation on EBIT. The new spectrometer has several advantages over the traditional grazing-incidence spectrometers for which components are constrained to lie on the Rowland circle. The spectrometer’s variable line-spaced grating has a dispersion plane that is nearly perpendicular to the incident radiation. This permits the use of a charge-coupled device (CCD) detector which is important given the low intensity of EBIT.

II. EXPERIMENTAL ARRANGEMENT

The design of the grazing-incidence spectrometer implemented on EBIT is based on an instrument developed at Ruhr-Universität Bochum, Germany, and is on loan from Auburn University, Alabama. A schematic diagram (Fig. 1)

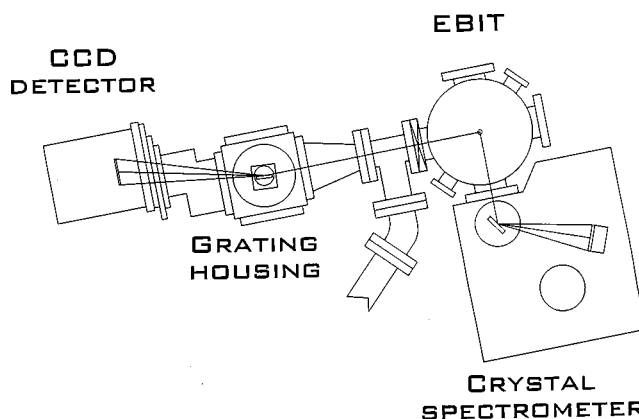


FIG. 1. Schematic diagram (top view) of the Auburn flat field spectrometer and the flat-crystal spectrometer indicating their position relative to EBIT. This arrangement permits the simultaneous acquisition of data using each of the systems. The AFFS spectrometer operates at a vacuum pressure of 1×10^{-6} Torr, therefore differential pumping is used between the grating housing and the high-vacuum EBIT trap region. In contrast, the flat-crystal spectrometer, operating at near 1×10^{-5} Torr, employs a thin foil window to isolate the gas load from EBIT.

displays the arrangement of the grating spectrometer and a flat crystal spectrometer at EBIT. The grating instrument, dubbed the Auburn flat-field spectrometer (AFFS), is centered around a $6.9 \times 6.9 \times 6.9$ in.³ aluminum cube with six ports and appropriate vacuum flanges. Inside this block is the grating mount which sits atop a rotatable stage which, in turn, is fastened upon a linear translation stage. These stages can be accessed from outside the vacuum chamber allowing for *in situ* adjustments of the position and angle of the grating. The housing is attached to an EBIT port via a vacuum duct with two slotted apertures that allow for differential pumping to reduce the gas load on the EBIT machine. To the aft of the central cube attaches an angled extension, matched to the nominal angle of reflection of the grating, to which the detector mounts. The AFFS utilizes a variable line-spaced, concave grating providing a nearly flat field of focus. This type of grating has been developed by Harada and Kita;^{5,6} it has an average line spacing of 2400 grooves/mm and a blaze wavelength of 15 Å. A grazing angle of incidence of 1.3° produces a focal plane that lies approximately 237 mm from the center of the grating, and is roughly perpendicular to the face of the grating. The focal plane covers a wavelength range from near 10–100 Å in a 30 mm region.

The AFFS design, based on a variable line-spaced grating, offers several advantages over traditional Rowland circle based spectrometers. Traditional soft x ray, grating spectrometers require that the entrance slit, grating, and detector be aligned on the cylindrical surface defined by the radius of curvature of the grating element so that the x rays strike the grating, and therefore the detector, at grazing incidence (see, for instance, Ref. 7). For film based spectrometers this poses no technical problems provided an adequate method for mounting the film on this cylinder is implemented. Film, though, has inherent problems itself in that it is typically insensitive to extreme low light levels and it requires additional steps for its development. The low light level of EBIT requires detectors sensitive to individual photons, i.e., photodiodes, multichannel plates (MCPs), and CCDs. Whereas photodiodes may be exactly aligned to the Rowland circle, they only view a small region, provide no spacial information, and must be used either as an array of many, or be scanned over a region of interest. MCPs and CCDs, while gaining spatial resolution, are typically planar and can, therefore, never be on the Rowland circle at all points. Often in this type of spectrometer such detectors are set tangentially to the circle so as to be in approximate alignment. However, while the geometry effects of the detector may be minimized this way, the efficiency of these detectors is usually diminished at grazing incidence. Moreover, moving the detector to access different wavelength regions means moving the detector along a complicated trajectory. By contrast, in the AFFS the photons strike the detector at nearly normal incidence along the entire detector plane producing a uniformly focused, broad spectral range. Different wavelength regions can be accessed by simple lateral motion of the detector.

Recording of the photons is accomplished by a Digital CCD Camera System, produced by Photometrics, which employs a one-inch square, thinned, back-illuminated, cryogenically cooled, CCD with a nominal pixel size of $25 \times 25 \mu\text{m}^2$.

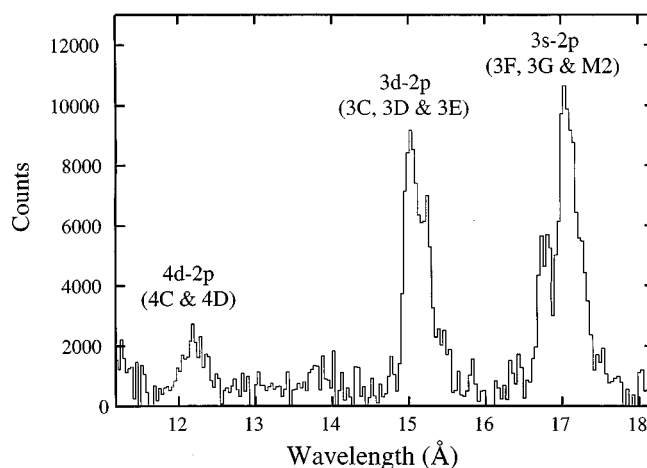


FIG. 2. A portion of the spectrum of Ne-like Fe^{16+} taken with the AFFS from 11.3 to 18.2 Å. With the spectrometer resolving power of about 70, $3d \rightarrow 2p$ is an unresolved blend of lines at 15.014, 15.261, and 15.453 Å (3C, 3D, and 3E, respectively). Similarly, the line marked $3s \rightarrow 2p$ is a blend of lines of wavelength 16.780, 17.051, and 17.096 Å (3F, 3G, and M2, respectively). Since this spectrum was obtained at grazing incidence, the parallel and perpendicular polarization components of the intensity are reflected with nearly equal efficiency.

The scientific-grade CCD is sensitive to x ray through near infrared radiation. Its two dimensional design provides spatial information about the structure of the beam plasma and allows binning of adjacent channels to increase the overall signal-to-noise ratio. The CCD is controlled by standard software and the data stored as binary files. Custom-written software allows the user to sum the spectra along the nondispersive direction of the CCD and to filter out spurious signals that come from either hard x rays or cosmic events.

III. MEASUREMENTS AND ANALYSIS

As a demonstration of the usefulness of the AFFS in conjunction with instrumentation already established on EBIT, measurements of soft x-ray lines of Fe XVII were made simultaneously with the AFFS at grazing incidence and a flat-crystal spectrometer at near 45° incident angle. Iron was injected into EBIT and ionized by a 1.1 keV electron beam, 150 eV below the energy required to make Fe XVIII, with a current of 41 mA in order to produce an ionic charge balance dominated by the neon-like charge state, Fe^{16+} . The wavelength scale of each instrument was calibrated using strong O^{6+} and O^{7+} lines present from background ions as well as N^{5+} and N^{6+} lines formed from nitrogen gas that is purposely injected into EBIT.

Spectra obtained using the AFFS were integrated for 30 min with a binning factor of 16. The CCD detector is sensitive to a broad range of radiation including hard x rays, which can pass through optical baffles, and infrared radiation, which reflects throughout the vacuum housing. Background spectra were alternately obtained under the same run conditions, but without the Fe injection, for later subtraction. At this setting, the wavelength region subtended by the detector ranged from less than 10 Å, the limit of the grating, to greater than 40 Å. Figure 2 shows a small portion of this

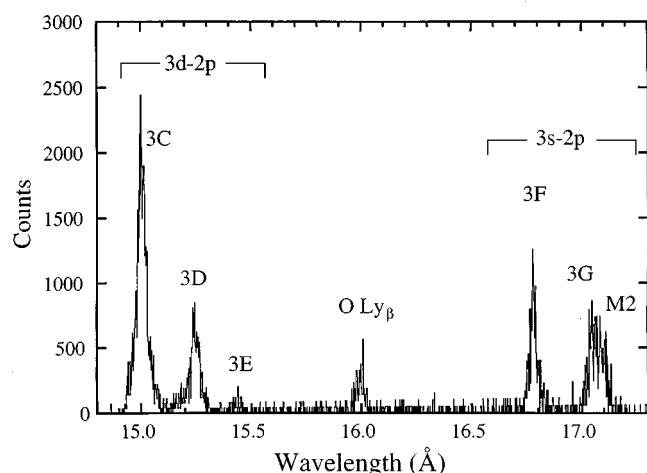


FIG. 3. Spectrum of Ne-like Fe^{16+} taken with a flat RAP crystal from about 15 Å to over 17 Å. Transition $3d \rightarrow 2p$ is resolved as lines 3C, 3D, and 3E. Similarly, of the lines marked $3s \rightarrow 2p$, the line 3F is resolved, but 3G and M2 remain blended. The resolving power for this instrument is about 600. Since this spectrum was obtained at an angle near 45° , unlike the parallel component, the perpendicular component was reflected with a very diminished efficiency.

range, after background subtraction, identifying the Fe XVII lines of interest near 15 and 17 Å. The $3d \rightarrow 2p$ transition comprises mainly three lines at 15.014, 15.261, and 15.453 Å, designated 3C, 3D, and 3E, respectively, in the notation of Parkinson.⁸ The $3s \rightarrow 2p$ transition is dominated by three lines at 16.780, 17.051, and 17.096 Å (3F, 3G, and M2).⁹ The resolving power of the AFFS is determined to be 70.

The crystal spectrometer employed a rubidium acid phthalate (RAP) crystal with $2d = 26.121$ Å. The detector subtended x rays with Bragg angles from 33.5° to 42° , corresponding to a wavelength range from 14.5 to 17.5 Å. Figure 3 shows a spectrum obtained within 40 min for Fe injection under the same conditions as above. The figure shows the same $3d \rightarrow 2p$ and $3s \rightarrow 2p$ transitions as in Fig. 2, but at a greater resolution. The position sensitive proportional counter used in this system is not sensitive to low energy radiation, and it may be gated to ignore high energy radiation. Therefore no background subtraction was necessary. However, spectra were obtained without Fe injection in order to identify lines arising from contaminant gases. The resolving power for this crystal spectrometer is about 600.

The polarization of the components of the $3s$ and $3d$ transitions directly affects the intensity of the lines when measured with the crystal spectrometer. The polarization is defined by the relative intensities of the parallel and perpendicular components as

$$P = (I_{\parallel} - I_{\perp}) / (I_{\parallel} + I_{\perp}). \quad (3.1)$$

Theoretical values for the polarization are derived from the fractional population densities of the magnetic sublevels³ and are used to derive a ratio of the absolute intensities of the lines from the measured intensities. The intensity of radiation observed at the detector is

$$I = R_{\parallel} I_{\parallel} + R_{\perp} I_{\perp}, \quad (3.2)$$

where R_{\parallel} and R_{\perp} are the reflectivities of the parallel and perpendicular components of the radiation, respectively. The ratio of the reflectivities,

$$R = R_{\parallel} / R_{\perp}, \quad (3.3)$$

is proportional to $\cos^m 2\theta$ where θ is the angle of incidence and m is a weighting factor, $1 < m < 2$, describing the quality of the crystal as perfect ($m = 1$) or mosaic ($m = 2$)³ (crystals used in this type of work typically have a value of near $m = 1.2$). For instance, polarization of $P = 0.0$ ($I_{\parallel} = I_{\perp}$) of a line measured with a crystal at 45° results in a measured intensity that is reduced to 50% of its actual value because the perpendicular component is not reflected. For a line of the same wavelength and intensity measured using the same crystal spectrometer, but a polarization $P = 0.5$ ($I_{\parallel} = 3I_{\perp}$), the intensity is only reduced by 25%. By contrast, the same lines dispersed with the grazing-incidence grating would be measured without such a reduction in intensity as the parallel and perpendicular components are approximately equally reflected. Using this information from the two spectrometers one can derive a formula to calculate a line's polarization provided the polarization of one of the other lines in the spectra is known. This two spectrometer technique was described in Ref. 3.

Comparing the AFFS spectrum with that from the crystal spectrometer, we note obvious discrepancies that we attribute to polarization of the lines. The polarizations of the $3d \rightarrow 2p$ transitions are known from theory to be $P_{3C,3D} = 0.40^9$ and are used as a normalization between the two spectra. The intensity of the 3F line relative to that of the $3d \rightarrow 2p$ transition is nearly the same in both spectra. It thus has nearly the same polarization as the $3d \rightarrow 2p$ lines. In particular, we infer its polarization to be $P_{3F} = 0.5 \pm 0.2$. The ratio of the long-wavelength $3s \rightarrow 2p$ transition (the 3G/M2 blend) relative to the $3d \rightarrow 2p$ transition is clearly larger for the AFFS spectrum than in the crystal spectrum, where it is measured near 40° Bragg angle. From this we infer the polarization of the feature to be $P_{3G,M2} = -0.5 \pm 0.2$. The uncertainty limits are set by the statistical quality of the spectra and the low resolution of the flat-field measurement. Moreover, light impinging on the surface of the CCD detector that arrives from reflections within the housing, but does not originate from the grating, creates a background that must be subtracted contributing to the possibility of systematic error. The present measurement, however, shows that flat-field, grazing-incidence spectrometers can be successfully and easily implemented on an EBIT complementing standard crystal spectrometer measurements in the soft x-ray region.

ACKNOWLEDGMENTS

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